TFAWS Aerothermal Paper Session

Optical Diagnostic Imaging of Multi-Rocket Plume-Induced Base Flow Environments

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Launch Vehicle Failures Due to Base Heating

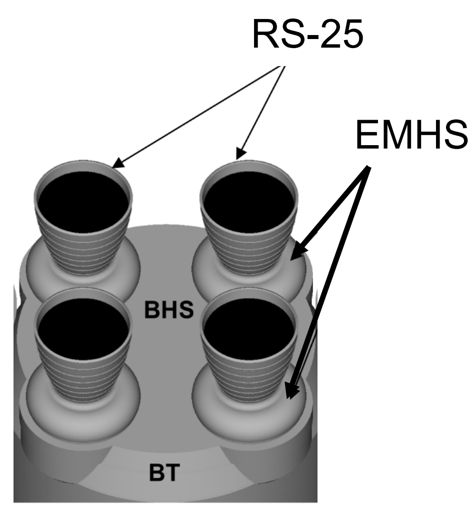
- Launch vehicles with multi-rocket engine base region
- Highly complex base flows due to changing multi-plume interactions and freestream flow
  - Difficulty in numerically predicting such environments
  - No analytical solution of this flow regime
- Base thermal protection system (TPS) protects avionics, wiring, engine gimbal actuators, turbomachinery, etc.
- Led to the failures of many launch vehicles due to vehicle control loss by not adequately predicting base environments

Rocket	Date	Outcome	Cause
JUPITER AM-1A	3/1/57	Failure	Base heating - Control Loss
ATLAS SM-65 A	6/11/57	Failure	Base heating - Control Loss
ATLAS SM-65 A	9/25/57	Failure	Base heating - Control Loss
THOR 114	1/1/58	Failure	Base heating - Control Loss
POLARIS A-1	12/30/58	Failure	Base heating - Control Loss
POLARIS A-1	1/9/59	Failure	Base heating - Control Loss
SATURN I	10/21/61	Concern	Base heating - Base Flow
SATURN IB	2/26/66	Concern	Base heating - Base Flow
SATURN V	11/6/67	Concern	Base heating - Base Flow
N-1 (SOVIET)	2/1/72	Failure	Base Flow - Roll Control
MAXUS (GERMAN)	5/1/91	Failure	Base heating - Control Loss
PROSPECTOR	6/19/91	Failure	Base heating - Control Loss

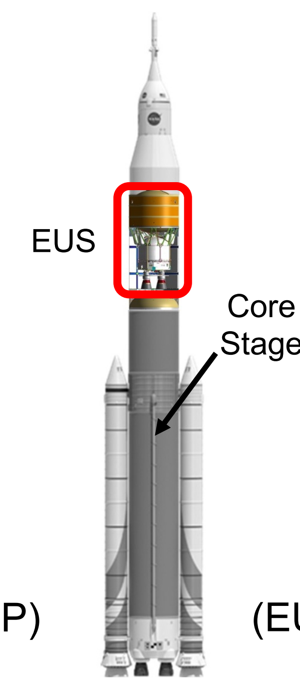


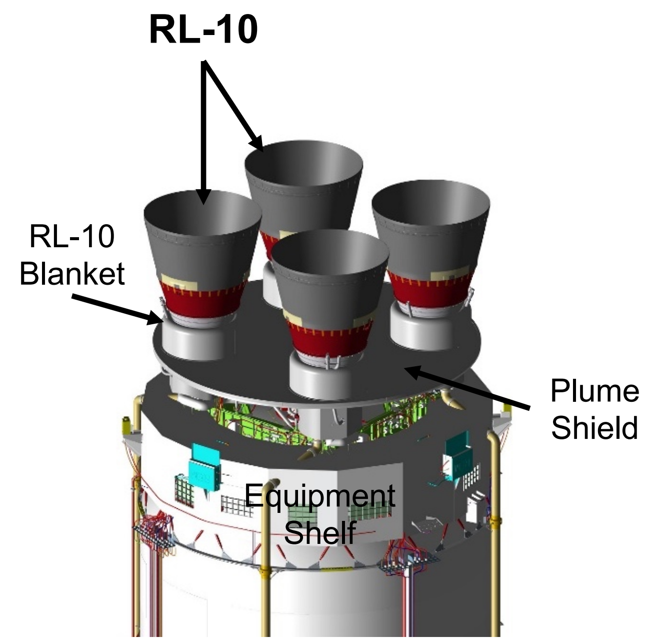

Short-Duration Base Heating Tests

- Both test programs were conducted at CUBRC Large Energy National Shock Tunnel I (LENS I) facility in 2016 to investigate launch vehicle base and plume flows
- FY16 TIP – 2% model; EUS – 3.23% model
- Rekindled NASA ground test techniques from the 1970s[1]
- Simulate >150,000 ft altitude conditions



Space Launch System (SLS) Core Stage Base
(FY16 Technology Innovation Program – FY16 TIP)

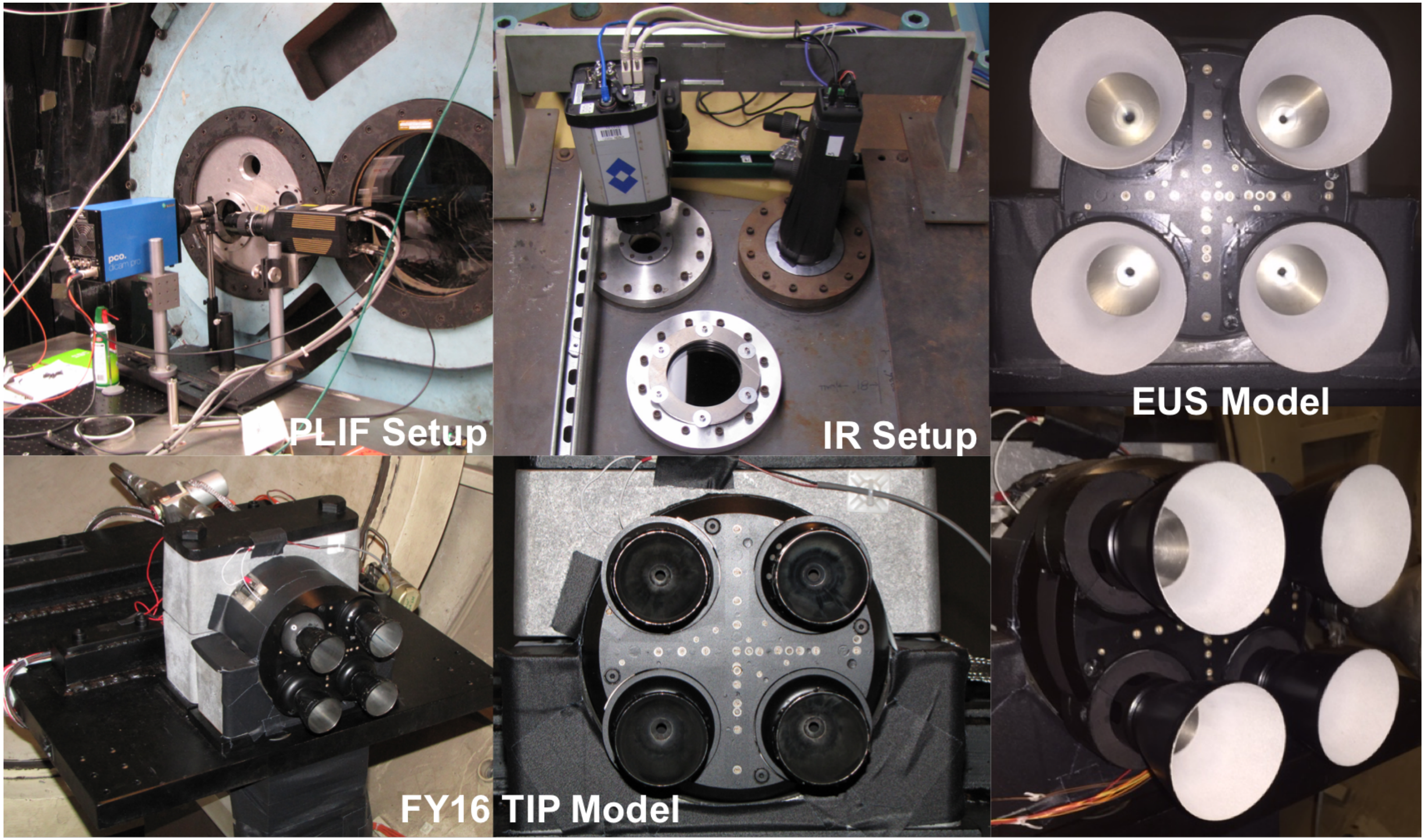




Exploration Upper Stage Base
(EUS Base Heating Test Program - EUS)

Short-Duration Test Propulsion Models

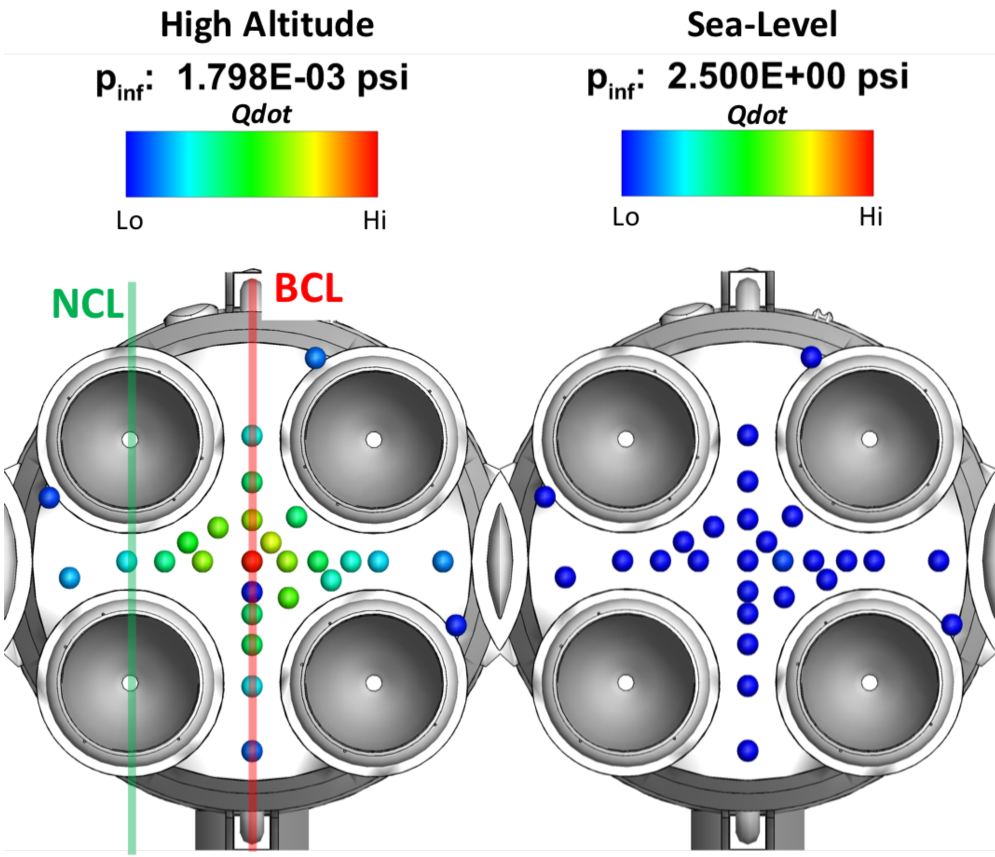
- NASA Marshall & CUBRC developed propulsion models for the SLS and EUS base heating test programs in a shock tunnel[2]
- Hydroxyl radical - planar laser induced fluorescence (OH-PLIF) and infrared (IR) imaging were used for the **first time** to visualize both base flow and plume environments



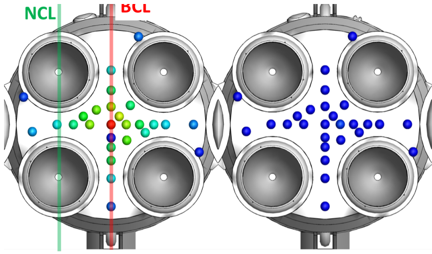
FY16 TIP Base Environments

- TIP main objective was to determine the feasibility to visualize and characterize base and plume environments for launch vehicle ascent flight using non-intrusive diagnostics in shock tunnel facility
- NCL = nozzle centerline, BCL = base centerline

- GO_2-GH_2 rocket engine performance (a,b,e,f)
- Base environments for sea-level and high altitude (~170,000 feet) conditions (c,d,g,h)
  - Thin-film heat transfer gauges
  - Piezo-resistive pressure sensors



FY16 TIP Base Environments



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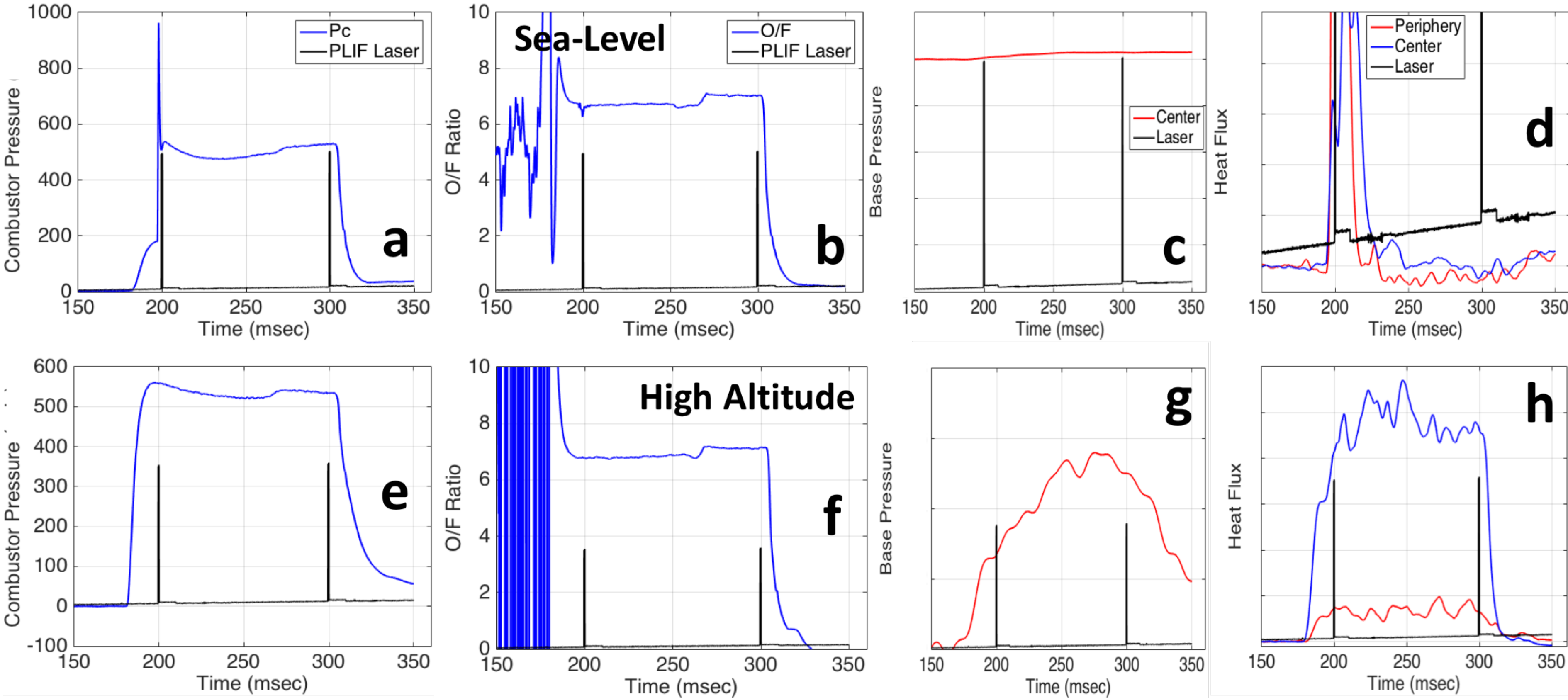
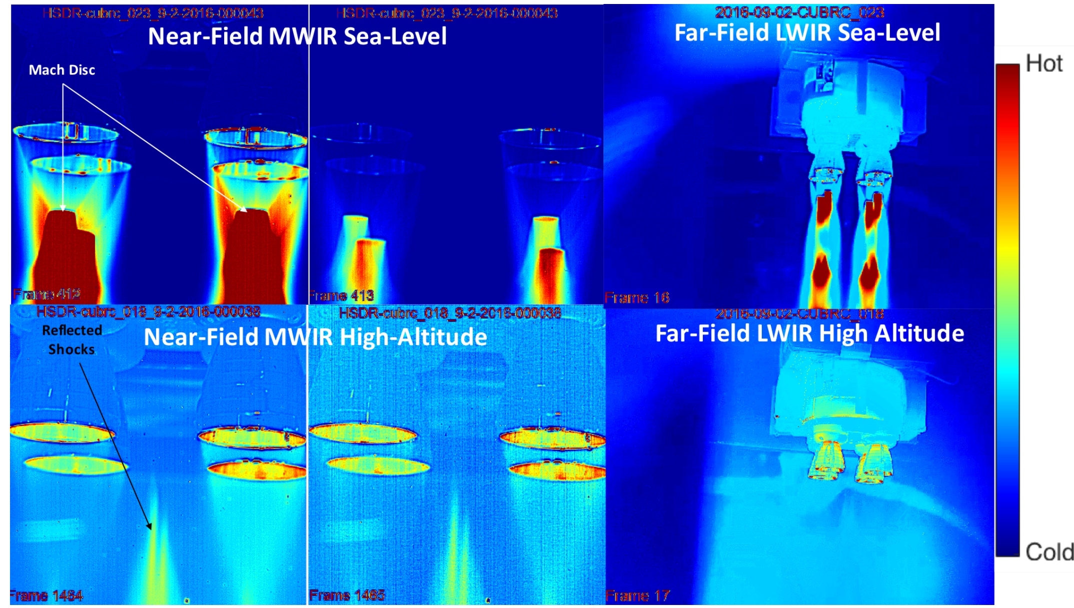
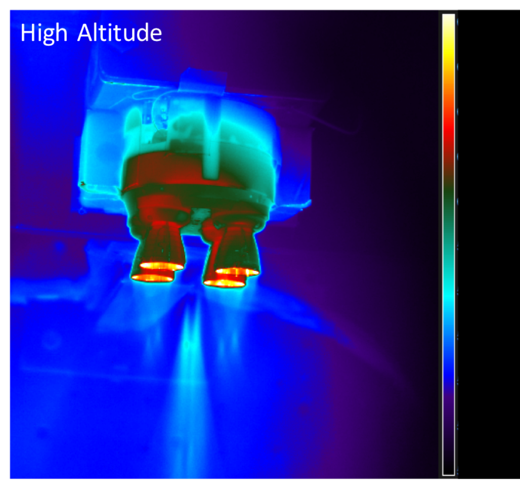


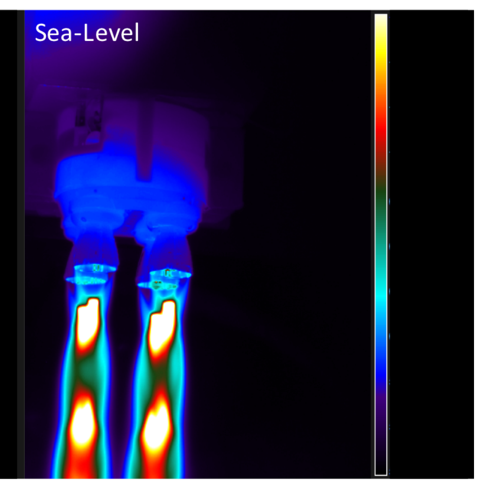
FY16 TIP IR Imaging

- Long-wave IR (7.5μm – 14μm) camera
  - Focused on the far-field
  - Calibrated for surface wall temperature characterization
- Mid-wave IR (3μm – 5μm) camera
  - Focused on the near-field
  - Ideal to visualize base flows
  - Low and medium temperature sensitive to distinguish flow features
- Different plume flow structures between high altitude and sea-level conditions



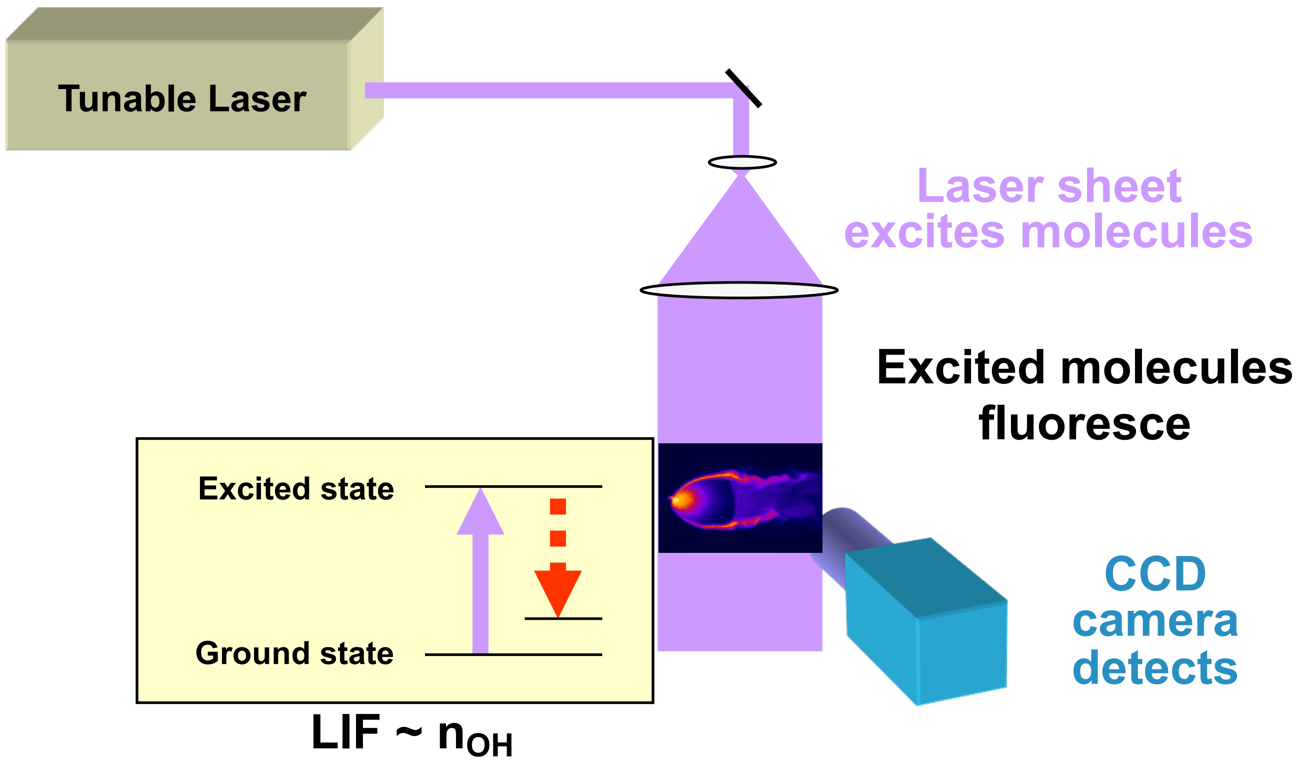


LWIR Low Temperature Range



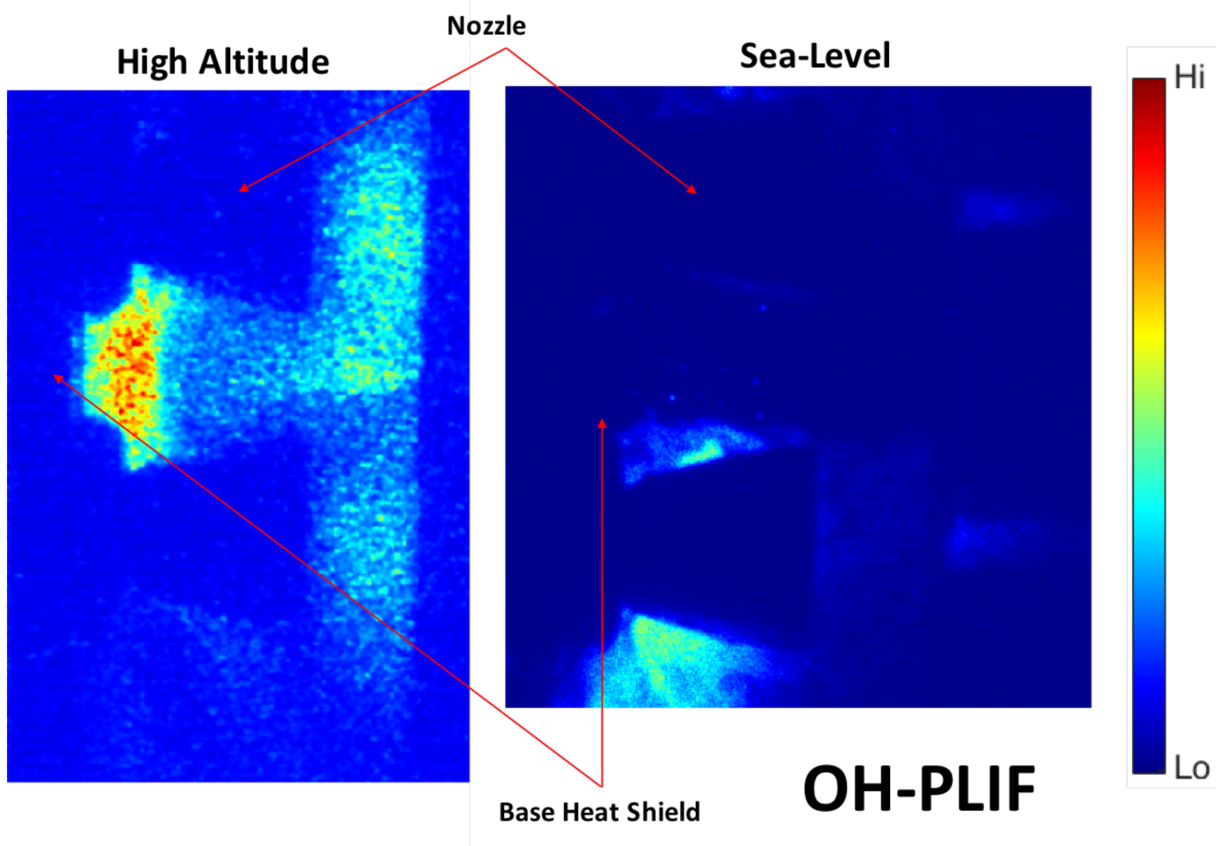
LWIR Low Temperature Range

Planar Laser-Induced Fluorescence (PLIF)[3-4]



FY16 TIP PLIF Imaging

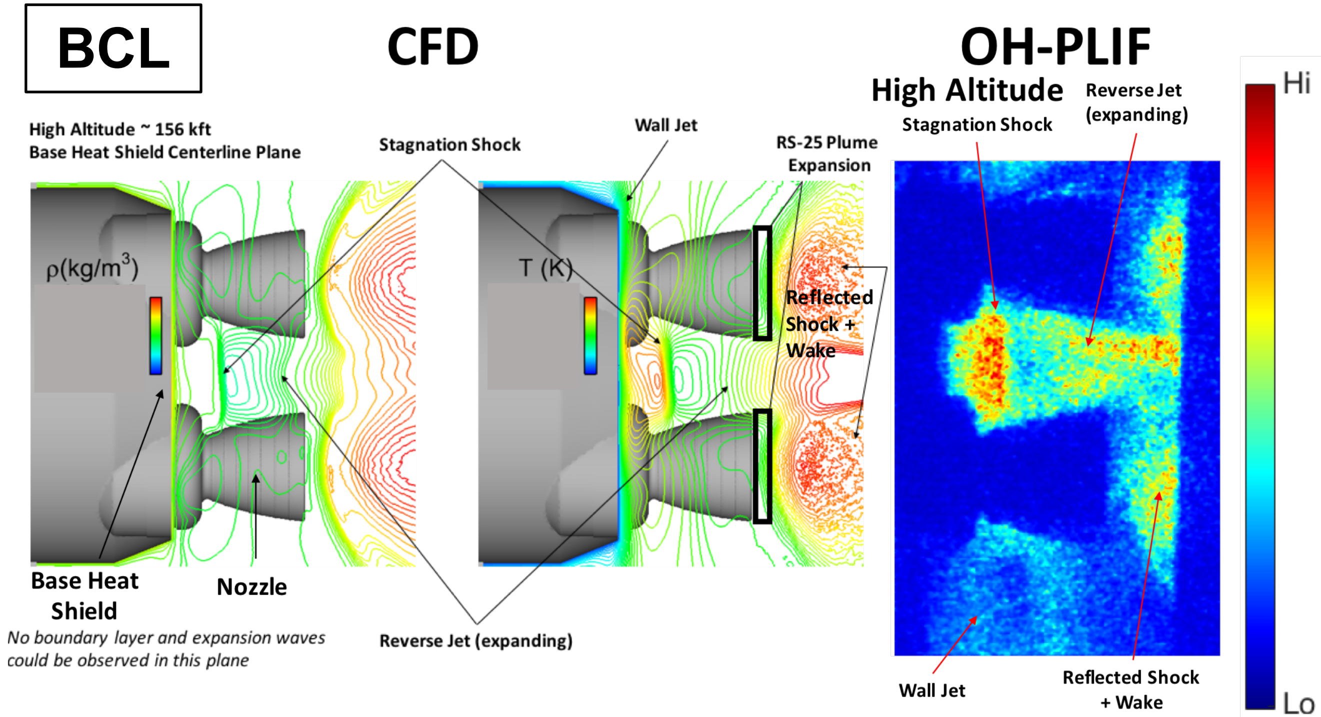
- Hydroxyl radical (OH) used as naturally occurring fluorescent tracer
  - Combustion intermediate species
- 10 ns Nd:YAG dye laser sheet at 20 mJ/pulse excites OH at 285.53 nm for flow visualization
  - Flow freezing images
- Two intensified CCD cameras with OH LIF transmitting filters were positioned normal to the laser sheet
- Different base flow structures observed between high altitude and sea-level conditions
  - Base flow structures not observed with CO_2– MWIR or schlieren imaging



FY16 TIP PLIF Imaging

- Base flow structures were successfully visualized using OH-PLIF
  - Shows OH emission intensity
  - Assuming constant mole fraction, frozen flow, extract **qualitative** gas temperature map
- Observe good qualitative agreement between test data and computational results
- Complex base flow structures
  - Stagnation shock
  - Reverse jet
  - Reflected shocks
  - Wall jet

- Need to assess stagnation shock RS-25 nozzle impingement region
- Shock impingement can augment heating by a factor of ~10
- Interaction first discovered by PLIF imaging



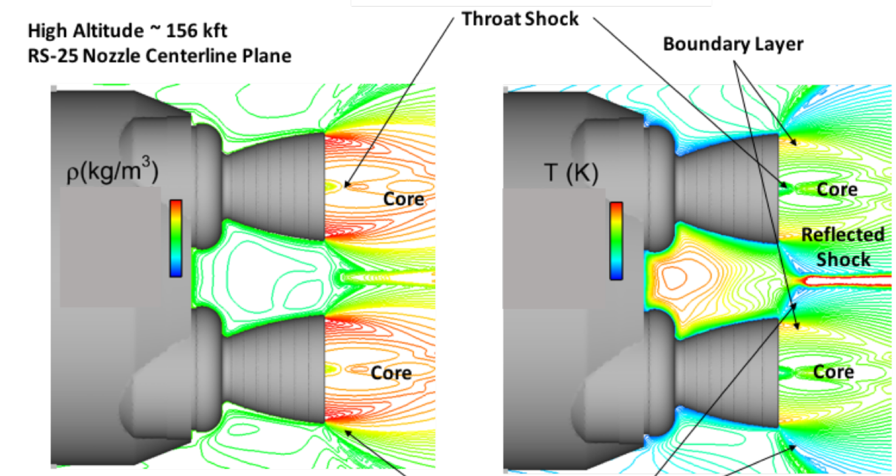
CFD solutions provided by F. Canabal (MSFC-EV33)

FY16 TIP PLIF Imaging

- Near-field plume flow structures were successfully visualized using OH-PLIF
- Observe good qualitative agreement between test data and computational results
- Complex plume flow structures
  - Hot boundary layer
  - Throat shock (cooler core flow)
  - P-M expansion waves

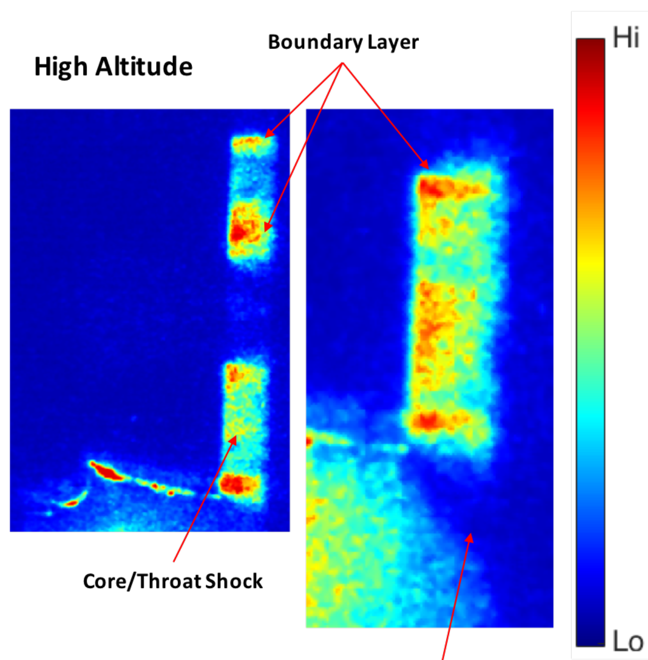
CFD

Observe core flow & reflected shock + wake using LWIR/MWIR



No reverse jet, stagnation shock or wall jet could be observed in this plane

OH-PLIF | **NCL**



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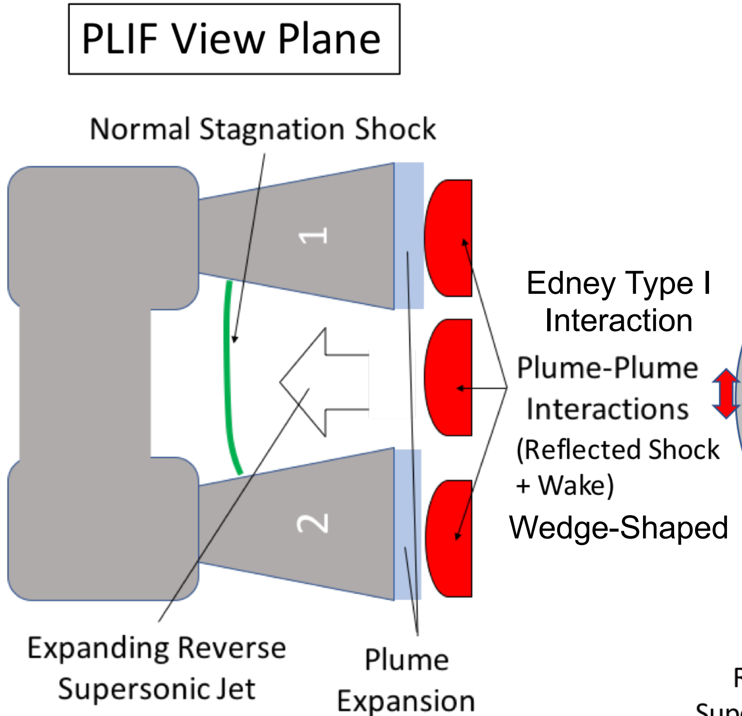
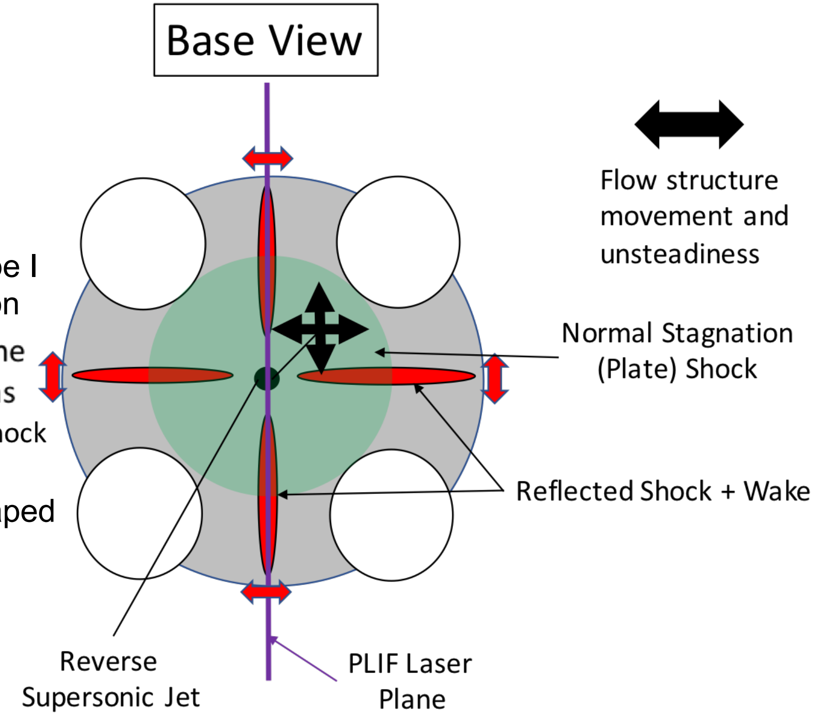
High-Altitude 4-Engine Base Flow Model

- Based on FY16 TIP imaging data analysis, 4-engine base flow model developed and builds upon existing base flow theories[5]
- Many unsteady flow structures lead to changes in the imaging data

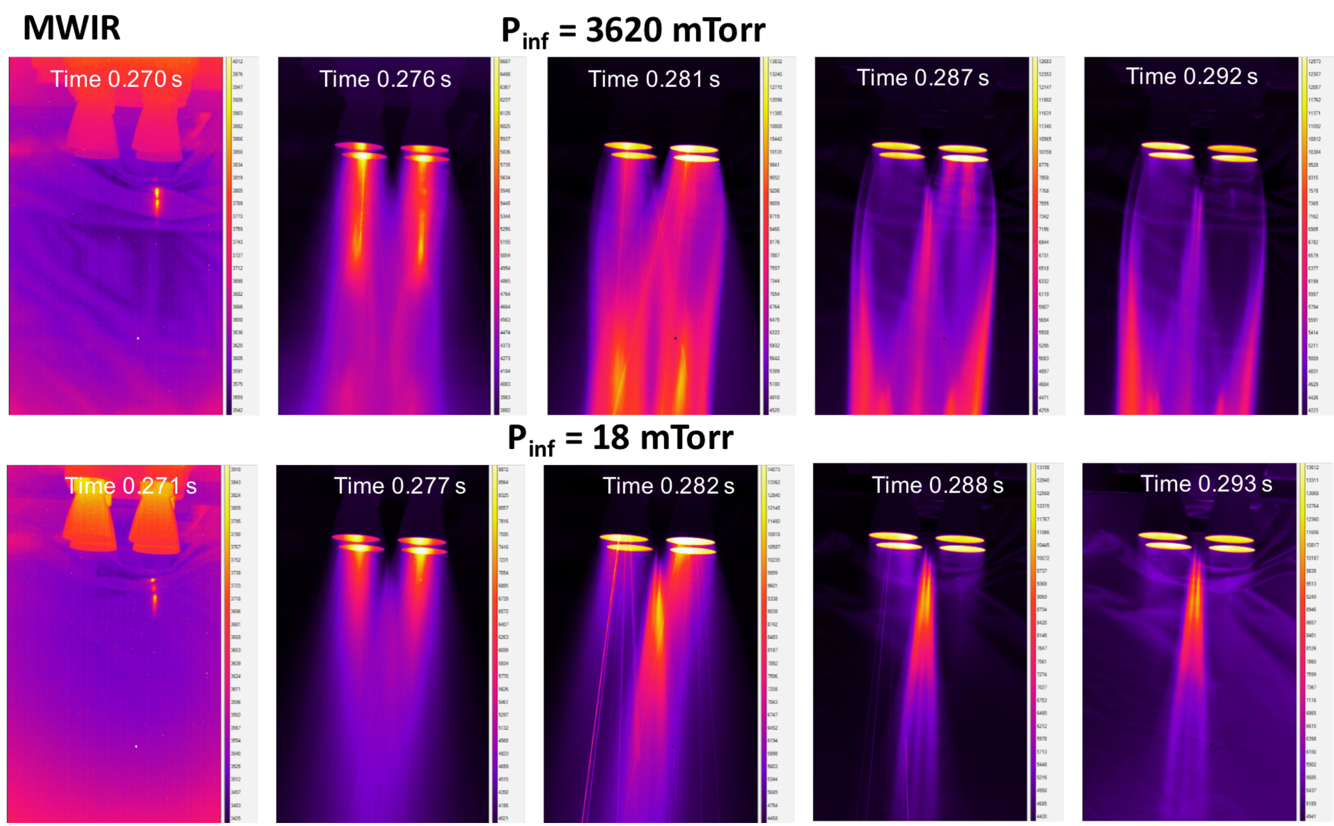




EUS IR Imaging

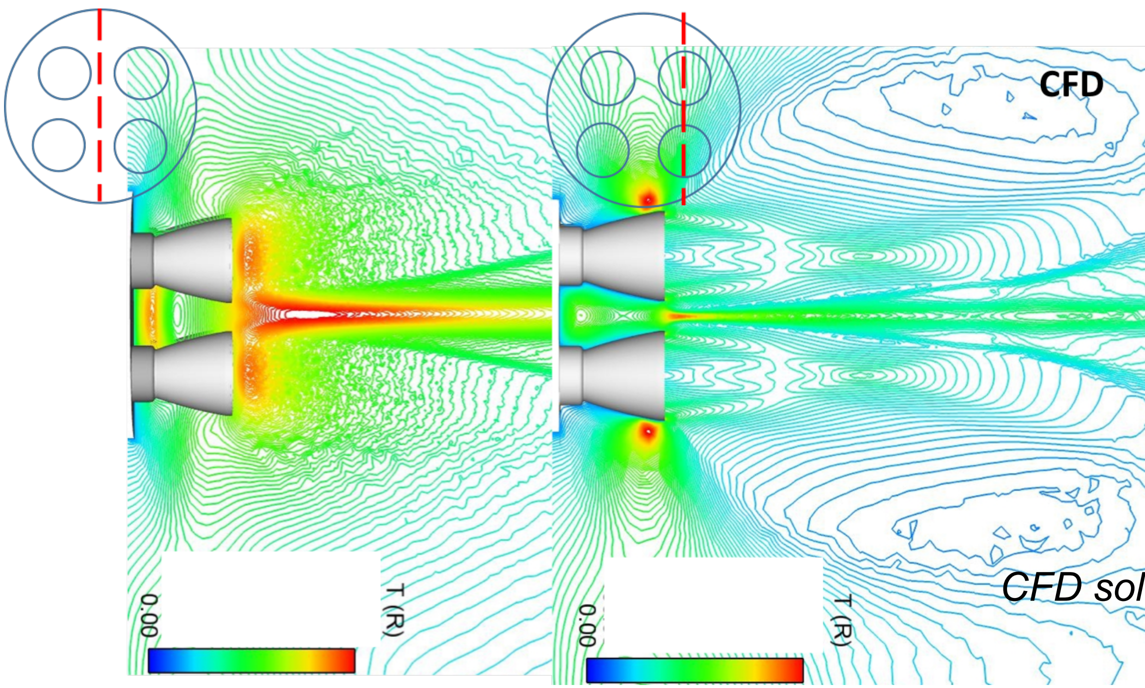
- EUS test main objective was to predict base convective heating environments and visualize base/plume flows using ground test data
- MWIR imaging of sub-scale EUS propulsion model start-up
- Observe differences in plume structure between sea-level and high-altitude conditions (~240,000 ft) within steady-state regime

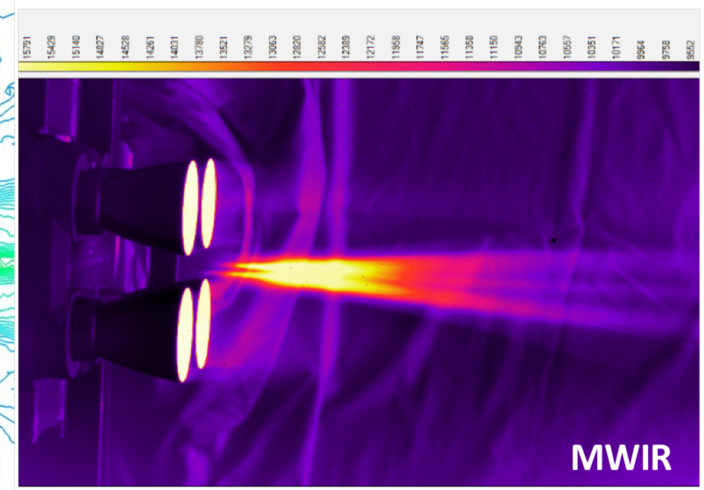
- Need optically thick hot gas to be observed with IR



EUS IR Imaging

- IR imaging is spatially averaged data taken between 100 Hz and 180 Hz
- Good qualitative agreement observed between IR data and computational solutions
- Major feature observed is the 4-lobed reflected shocks and their wake

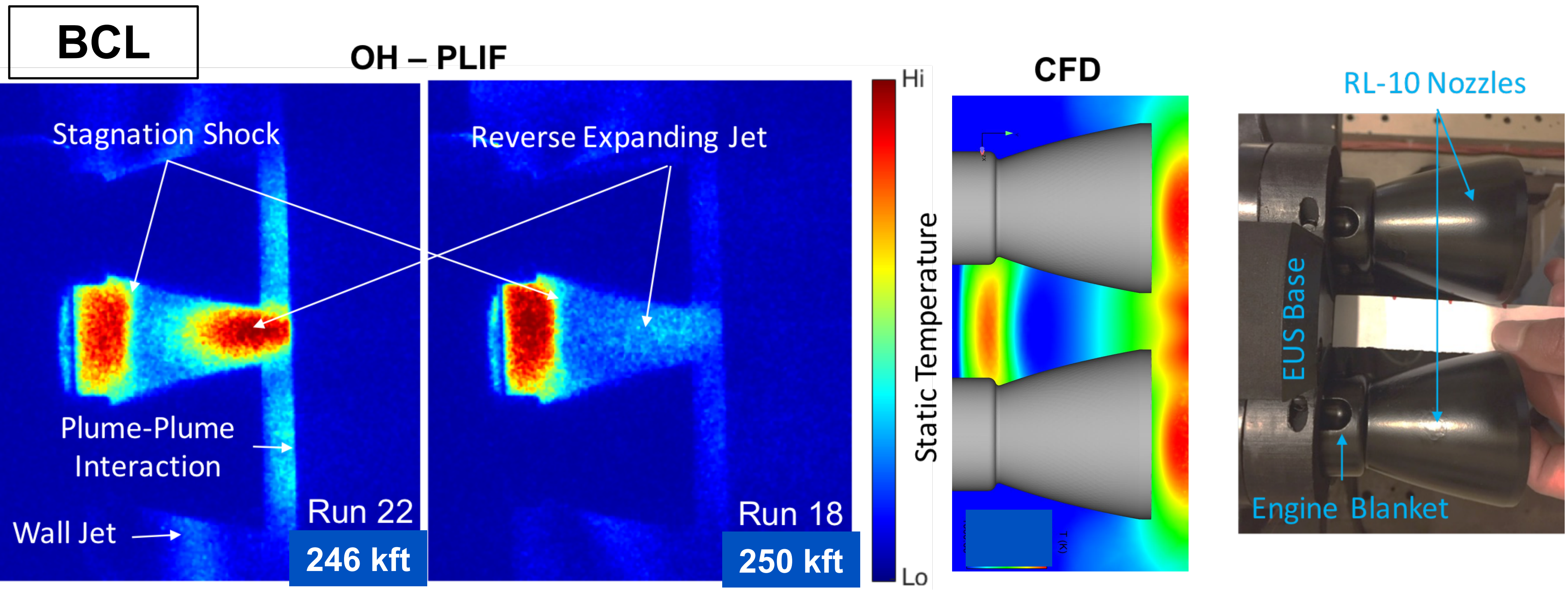




CFD solutions provided by C. Lee (MSFC-EV33)

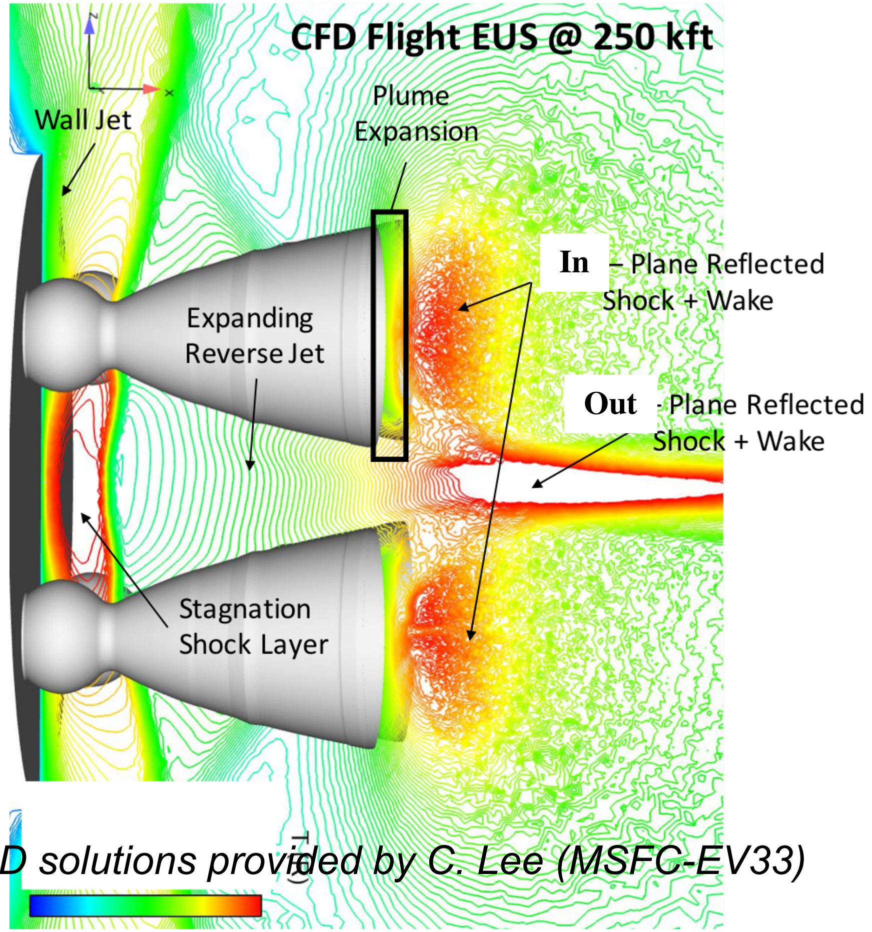
EUS PLIF Imaging

- Good qualitative agreement observed between PLIF data & computational solutions
- All major base flow structures observed
  - Similar to SLS core-stage base flow (TIP) and confirms 4-engine base flow model
- Similar flow structures and qualitative trends observed between ground test data and CFD



EUS Test PLIF – Flight CFD Comparison

- Observe similar flow structures between ground test PLIF imaging, test model CFD and flight CFD solutions
  - Similar concave stagnation shock structure, stand-off distance and shock diameter
  - Similar in-plane reflected shock contours
  - Similar expanding reverse jet
- Suggests sub-scale ground test simulates appropriate flow physics to flight
  - Provides further confidence in plume-induced flight environments based on ground test
- Need to assess stagnation shock - RL10 nozzle impingement



CFD solutions provided by C. Lee (MSFC-EV33)

PLIF Thermometry

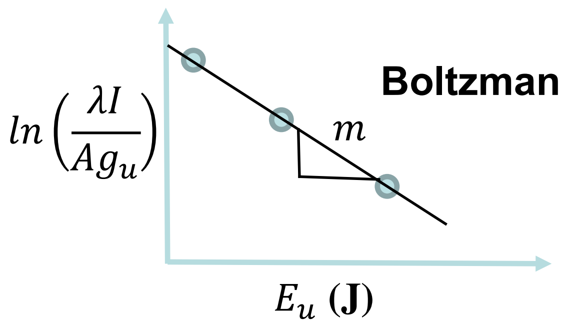
- $ln\left(\frac{\lambda I}{A g_u}\right) = \frac{-E_u}{kT} + C_1$ where λ, A, g_u, E_u, k, C_1, I

and T are the targeted wavelength, transition probability (Einstein coefficient), multiplicity of the upper state, excited state energy, Boltzmann constant, linear equation constant, measured line intensity and excitation temperature

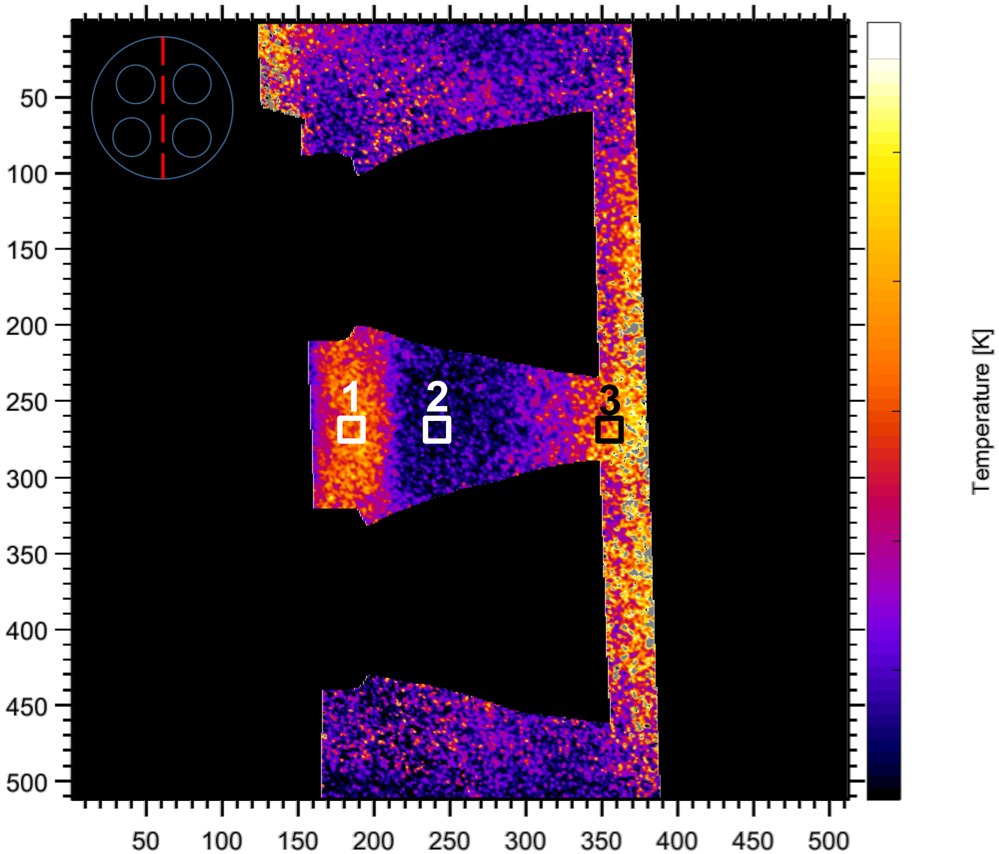
- $S = \lambda I; C = A g_\mathrm{u}$
- $m = \frac{-1}{kT}$ (slope of $ln\left(\frac{S}{C}\right)$ vs. E_u plot)
- A, g_u, E_u, k are determined from handbooks of spectroscopic constants, chemistry and physics
- λ, I are obtained from the test program
- From the slope of the Boltzmann plot, temperature of the targeted gas can be estimated

5 test runs were used at three λ targets

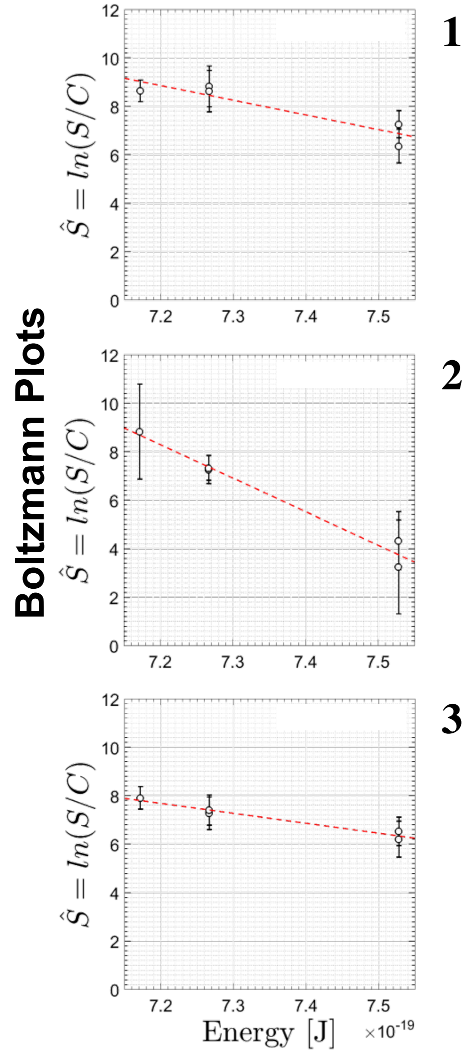
Run #	name	J	λ (nm)
39	Low J	Q2(6)	283.380
22	mid J	Q1(8)	283.553
23	High J 1	Q2(12)	285.545
24	High J 2	Q2(12)	285.545
8	mid J	Q1(8)	283.553



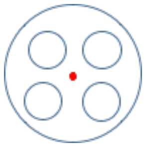
PLIF Thermometry



EUS Thermometry – Interrogation – Window 2 x 2



EUS GT Base Static Temperature Distribution



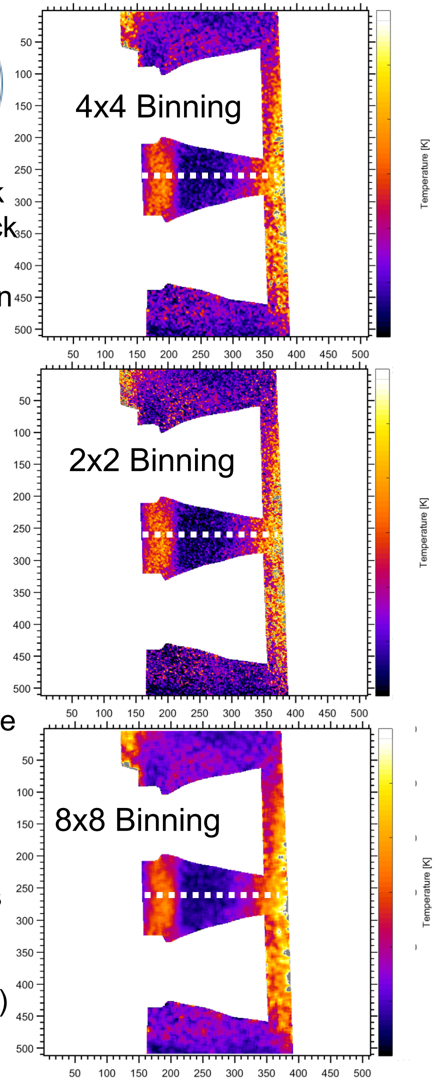
T1 = Temp Pre Stagnation Shock
T2 = Temp Post Stagnation Shock

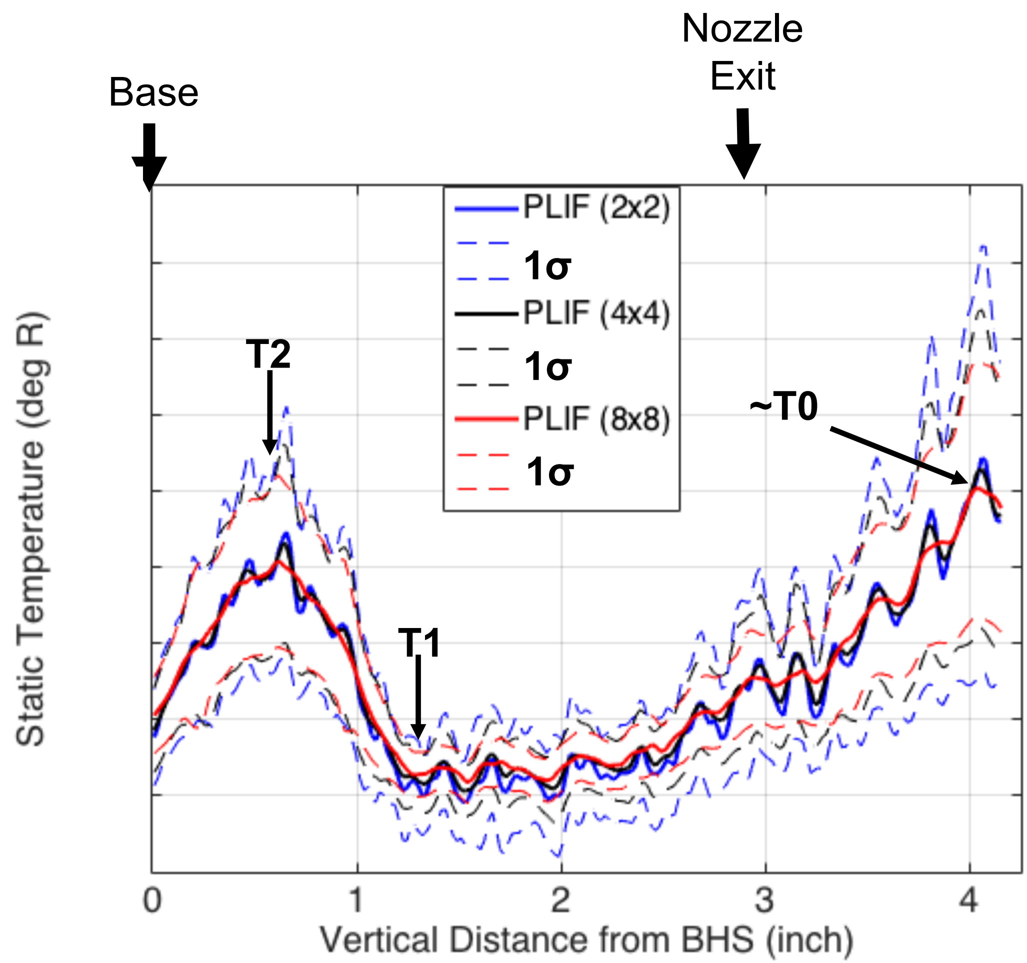
- Temperature distribution taken along the center of the plume shield to just past the nozzle exit as shown in the dotted white line

- Binning was conducted to obtain mean values and uncertainty statistics of the thermometry PLIF 2D data

- 2x2 binning = uncertainty statistics and mean value were obtained from surrounding 4 pixels

- Dark solid lines are mean distributions and dashed lines are the uncertainty distributions for three binning techniques (2x2, 4x4 and 8x8)





Conclusions

- TIP & EUS test programs provided for the first time proof-of-concept and technical maturation of non-intrusive diagnostics of visualizing and characterizing complex reacting plume-induced base flows in a ground test facility

- Led to an increase in the technology readiness level (TRL) for short-duration hot-fire test technique and improves confidence in plume-induced flight convective environment predictions

- In the process of developing EUS and SLS base gas temperature maps from PLIF thermometry
  - Historically, experimental base gas temperature data has the highest uncertainty and limited flight data and no temperature map has been obtained to date
  - First time develop a temperature data map of this region to increase the fidelity of base convective heating predictions

References

- [1]Bender, RL, Lee, YC (1978), IH-39 Base Heating Test Data Analysis, NASA CR NAS8-29270, RemTech Inc., Huntsville, AL
- [2]Mehta, M, (2014), Space Launch System Base Heating Test: Sub-Scale Rocket Engine/Motor Design, Development and Performance Analysis, AIAA 2014-1255, 52nd AIAA SCITECH, National Harbor, MD.
- [3]Johansen, CT, McRae, CD, Danehy, PM, Gallo, E., Magnotti, G., Cutler, A., Rockwell, RD, Goyne, CP, McDaniel, JC (2014), OH PLIF Visualization of the UVa Supersonic Combustion Experiment: Configuration A, *Journal of Visualization*
- [4]Danehy, PM, Inman, JA, Alderfer, DW, Buck, GM and Bathel, B (2008), Visualization of Flowfield Modification by RCS Jets on a Capsule Entry Vehicle, AIAA 2008-1231, 46th AIAA SCITECH, Reno, NV.
- [5]Brewer, EB and Craven, CE (1969), Experimental Investigation of Base Flow Field at High Altitude for a Four-Engine Clustered Nozzle Configuration, NASA Technical Note, NASA TN D-5165. Led to an increase in the technology readiness level (TRL) for short-duration hot-fire test technique and improves confidence in plume-induced flight convective environment predictions